ECONOMICS OF FUEL CYCLE AND WASTE MANAGEMENT SYSTEMS
HIGH LEVEL WASTE PART II

E. Johnson, Chair
R. DeWames, Co-Chair

A COMPARATIVE STUDY OF RADIOACTIVE WASTE EMPLACEMENT CONFIGURATIONS[a]

L. W. Scully
Sandia National Laboratories[b]
Albuquerque, NM 87185

H. F. Gram
M. L. Wheeler
R. I. Brasier
Los Alamos Technical Associates, Inc.
Los Alamos, NM 87544

ABSTRACT

Three waste emplacement configurations have been evaluated in the development of a repository design for the Nevada Nuclear Waste Storage Investigations Project. The evaluation considers a unit cell containing 1,000 canisters of spent fuel, configured in various ways to assist in identifying a waste emplacement method that is dependable, cost-effective, and safe. Five categories of factors affected by the emplacement configuration are evaluated against seven criteria. Each configuration results in significantly different drift layouts and dimensions which, in turn, affect the volume of mining and drilling, the dissipation of heat, ventilation requirements, cost, worker hazards, environmental impact, and resource commitments. The evaluation showed that further development of the self-shielded package concept is not warranted. Horizontal emplacement arrays offer significant advantages over vertical emplacement arrays, and the development of prototype equipment for horizontal emplacement is clearly justified. Vertical emplacement has been examined in a number of earlier studies, and it is recommended that further work in this area be delayed until the technology for horizontal emplacement can be developed to a state comparable with the existing technology for vertical emplacement.

PURPOSE OF THE STUDY

The Nevada Nuclear Waste Storage Investigations (NNWSI) Project is part of a program administered by the U.S. Department of Energy (DOE) Office of Civilian Radioactive Waste Management. The agency is responsible for developing and constructing a geologic repository for the permanent isolation of spent reactor fuel, high level radioactive waste, and transuranic (TRU) waste produced by commercial nuclear fuel cycles. A major goal of the NNWSI Project is to evaluate a site in welded tuff more than 100 m above the water table at Yucca Mountain on or near the Nevada Test Site. To assist in this effort, a site-specific repository conceptual design is under development. The engineering design of the repository is directly dependent on the choice of emplacement configuration. The three waste emplacement configurations under consideration are illustrated in Fig. 1. They are

- the self-shielded package (SSP), which consists of cylindrical, self-shielding steel canisters, placed at intervals on the floor of the drift,
- vertical emplacement of single canisters in a series of boreholes drilled in the drift floor, and
- horizontal emplacement of many canisters in long horizontal boreholes drilled in the drift walls.

Conceptual design assessments indicated that the SSP would be more costly in meeting Nuclear Regulatory Commission requirements[1] than alternative waste package designs, and it is recommended that the concept not be developed further.[2] Other preliminary evaluations also indicate that horizontal emplacement may have at least two advantages over the other configurations: (1) the temperature of unventilated emplacement drifts is significantly lower than for the SSP and vertical emplacement configurations, and (2) horizontal emplacement requires much less mining and drilling. The choice of an emplacement method required a thorough and systematic evaluation of each configuration to establish the relative advantages and disadvantages; this was the subject of a study conducted by Sandia National Laboratories and Los Alamos Technical Associates, Inc. This paper summarizes the findings reported in that study.[3]

METHOD OF EVALUATION

The comparison of the three configurations was based on a systems engineering assessment of factors

---

[a] This work was supported by the U.S. Department of Energy (DOE) under Contract DE-AC04-DP00789.

[b] A U.S. DOE Facility.

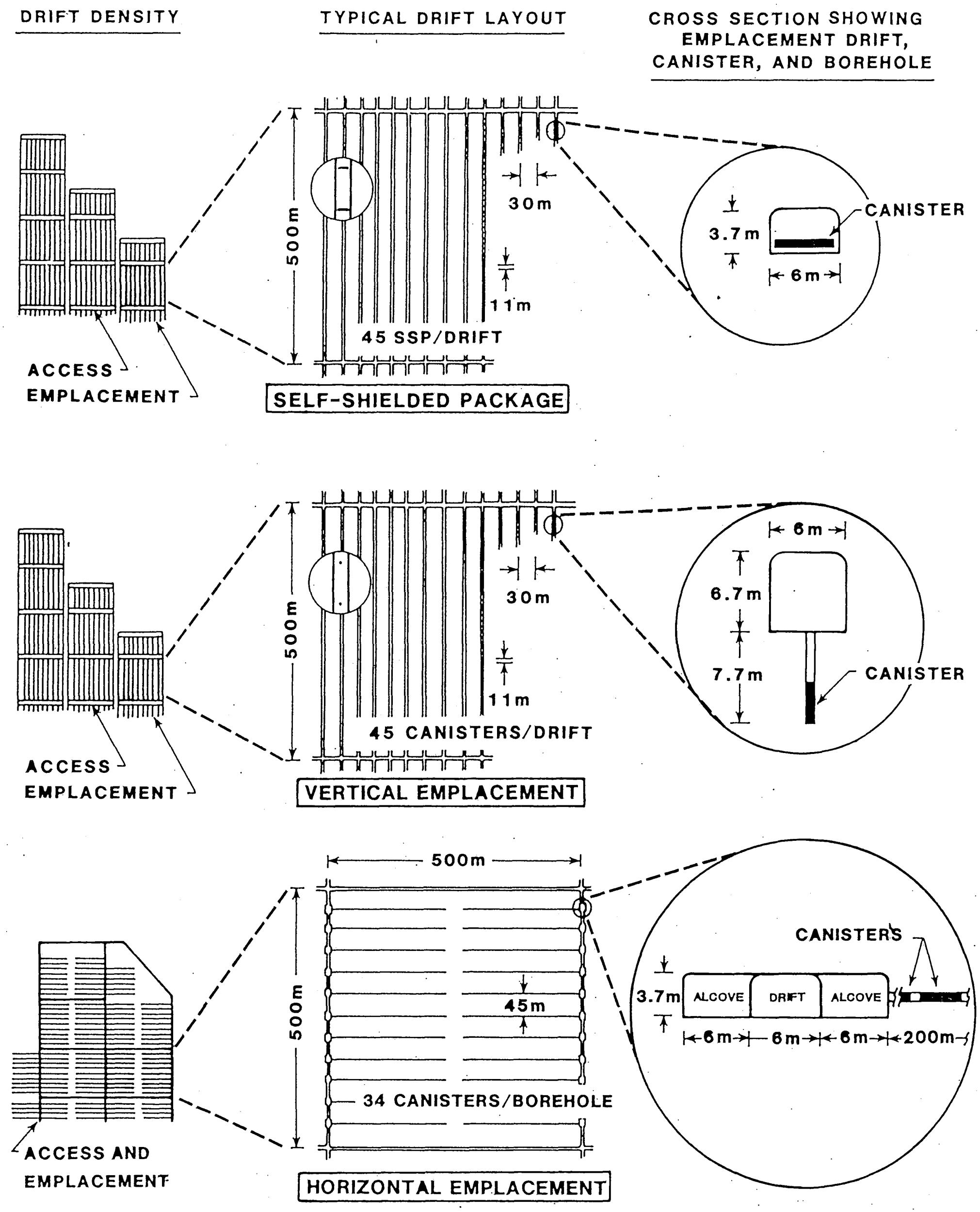

Fig. 1. Comparison of waste emplacement configuration layouts based on 50 kW/acre gross thermal load.

and criteria that affect repository design. Five factors were identified as requiring evaluation. They are

- waste package characteristics,
- quantity and distribution of heat deposited by the waste in the host rock and the influence of this heat on the ability of the repository to contain and isolate the waste,
- mining and ventilation requirements,
- waste emplacement and retrieval equipment design and operation, and
- repository sealing procedures.

These factors were evaluated against seven criteria selected because of their impact on the ability of the repository system to perform in a dependable, safe, and cost-effective manner. The criteria are quantitative or qualitative, depending upon which factors are influenced by the emplacement method. The evaluation criteria are

- reliability,
- flexibility,
- worker hazard,
- environmental impact,
- resource commitment,
- scheduling, and
- cost.

The evaluation matrix is shown in Fig. 2. In each block, either the type of data used in the evaluation process or the designator NA (for evaluations that are not applicable) is shown. NA is used for any of three reasons: there is no connection between the factor and the criterion; there is no difference among emplacement configurations, or the difference is judged to be small enough to be ignored for purposes of this study; and the comparison duplicates one identified elsewhere in the matrix.

Where applicable, comparisons were based on 1,000 canisters of "reference" spent fuel each with a thermal output of 3.4 kW at the time of emplacement. This exceeds the thermal output of other waste types, and provides a conservative basis for selecting a waste emplacement configuration. The maximum areal power density for the repository was assumed to be 50 kW/acre.

RESULTS OF ANALYTICAL STUDIES

Supporting studies were done to provide data needed for comparing emplacement configurations. These consisted of (1) thermal and thermal-structural stability studies to determine the influence of decay heat, (2) mining and ventilation requirements to determine relative excavation requirements and nonthermal structural limitations, and (3) repository operations studies to establish equipment and labor requirements and the worker hazards associated with each configuration.

Thermal Studies

Analytical and/or numerical calculations were made of the spatial and temporal temperature

LEGEND
DEG = DEGREE
I = INJURIES
ID = INJURIES AND DOSES
ΔT = CHANGE IN TEMP
NA = NOT APPLICABLE

CRITERIA / EVALUATION FACTORS	WASTE PACKAGE		THERMAL-STRUCTURAL ANALYSIS		REPOSITORY					OPERATIONS				SEALING	
					MINING		VENTILATION			EMPLACEMENT		RETRIEVAL		BACKFILL	
	FABRICATION	MATERIALS	THERMAL HYDROLOGY	THERMAL-STRUCTURAL STABILITY	DRIFTS	BOREHOLES	MINING	EMPLACEMENT	RETRIEVAL	LABOR	EQUIPMENT	LABOR	EQUIPMENT	AT EMPLACEMENT	AT CLOSURE
RELIABILITY	NA	NA	DEG	ΔT STRESS	NA	DEG	NA	DEG	DEG	NA	DEG	NA	DEG	DEG	DEG
FLEXIBILITY	DEG	DEG	NA	ΔT	NA	DEG	NA	DEG	DEG	NA	DEG	NA	DEG	DEG	DEG
WORKER HAZARD	I	NA	NA	NA	I	I	NA	NA	NA	ID	NA	ID	NA	ID	NA
ENVIRONMENTAL IMPACT	NA	NA	NA	NA	VOL SPOIL	VOL SPOIL	NA	NA	NA	NA	NA	NA	NA	NA	NA
RESOURCE COMMITMENT	NA	TONS OF STEEL	NA	NA	KW	KW	KW	KW	KW	NA	NA	NA	NA	NA	NA
SCHEDULING	NA	NA	NA	NA	DEG	DEG	NA	NA	NA	NA	DEG	NA	DEG	DEG	NA
COST	$	$	NA	NA	$	$	$	$	$	$	$	$	$	$	$

Fig. 2. Data requirements for comparing emplacement configurations.

distributions around the waste canisters for each configuration.[4] From these calculations, three critical parameters were identified as having the greatest impact on repository design:

- Temperature of the Waste Package--The effect of waste package temperature on waste form or container degradation, emplacement and retrieval operations, and the performance of the borehole liner used for horizontal emplacement is of concern. The calculated temperatures are shown in Fig. 3.

- Temperature of Unventilated Access or Emplacement Drifts--The time-history of drift temperatures influences the structural stability of the drifts, as well as the need for ventilation during emplacement or retrieval operations. Average drift temperature as a function of time for unventilated emplacement drifts are presented in Table I.

- Heat Flux into Ventilated Drifts--The ventilation required to maintain acceptable working conditions in the drifts is determined by heat flow. The calculated heat flux for the area of drift required to emplace 1,000 canisters is shown in Fig. 4. Heat flux into ventilated emplacement drifts varies with time and emplacement method. For this analysis, all emplacement drifts were assumed to be open (no backfill) and ventilated to maintain a constant air temperature.

The differences in temperature history and heat flux among the three configurations is directly related to the separation distance between the waste canisters and the open drifts. As the separation distance increases, the mass of rock available to absorb and dissipate heat increases. Consequently, as shown in Fig. 4 and Table I, heat flux and drift temperatures are highest for the SSP, intermediate for vertical emplacement, and lowest for horizontal emplacement.[4] The reverse is true for waste package temperatures, as shown in Fig. 3.

All three parameters show a clear advantage for horizontal emplacement over the other two configurations. The higher waste package temperatures would

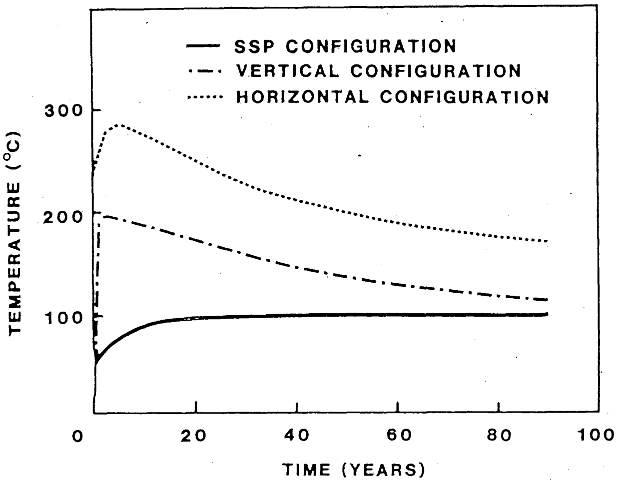

Fig. 3. Waste package surface temperature vs time.

TABLE I

Temperature of Unventilated Emplacement Drifts[a]

Time (Years)	Emplacement Method (Temperature, °C) SSP	Vertical	Horizontal
0	25	25	25
10	79	66	28
20	88	84	33
30	92	NC	38
40	94	NC	45
50	95	NC	NC
60	NC[b]	NC	56
70	NC	NC	NC
80	NC	95	63
90	94	NC	NC
100	NC	NC	68

[a] Elapsed times were not identical in all analyses.

[b] NC means not calculated.

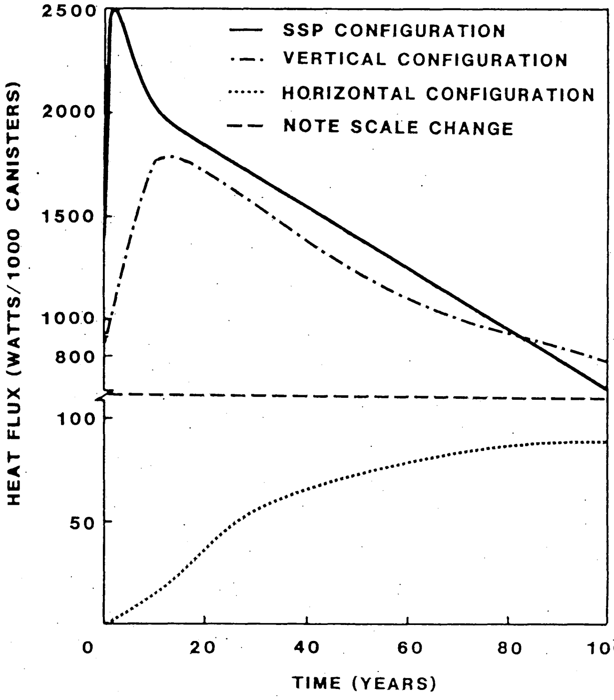

Fig. 4. Heat flux into ventilated drifts.

delay the onset of container corrosion by prolonging the presence of a dehydrated zone around the emplacement location. Lower drift temperatures and heat flux result in lower ventilation requirements. The lower temperatures of the unventilated drifts also reduce thermal effects on structural stability.

Thermal-Structural Stability

Thermomechanical effects on the emplacement drifts for the vertical and horizontal concepts were analyzed for both unventilated and ventilated conditions.[5] No thermomechanical analysis of the SSP configuration was performed; however, calculated temperature distributions around the emplacement drift are similar to those for the vertical emplacement configuration. By inference, the thermomechanical effects would also be similar.

The studies indicate that the same degree of potential joint movement exists for both vertical and horizontal configurations. Most of the movement is associated with excavation. Conventional rock-bolt and wire-mesh technology would be adequate for structural support.

The evaluation also indicates a potential for development of horizontal tension cracks in the walls of the horizontal drifts; this would have to be considered in the design of the borehole closures. Stress redistribution may occur due to cracking in areas where the thermal gradients are greatest. The steel borehole liner would adequately address this concern.

The waste package temperature history for horizontal emplacement shows that the existence of a dehydrated zone around the waste will last much longer than in the SSP and vertical configurations.[4] This dehydrated condition may reduce canister corrosion rates. For all three configurations, thermally driven moisture flux into drifts would be well within the rate of moisture extraction by the ventilation system, so no moisture condensation is predicted.[6]

Mining and Ventilation Requirements

The mining, drilling, and ventilation requirements for the three configurations are summarized in Table II. Horizontal emplacement has significantly lower requirements than the other configurations due to the reduction in drift length and lower heat flux.

Repository Operations

The reduced mining requirement for horizontal emplacement significantly reduces the labor requirement and the directly related worker hazards. The equipment requirements differ among the emplacement alternatives, particularly with regard to borehole construction and waste emplacement. The drilling of short vertical boreholes and related waste emplacement can be accomplished by modifying existing drilling and waste handling equipment. The drilling of long horizontal boreholes would require development of specialized equipment. Similarly, waste emplacement and retrieval operations would require the development and demonstration of a specialized waste transport/emplacement vehicle.[7]

COMPARISON OF ALTERNATIVES

In comparing the configurations, cost, worker hazard, environmental impact, and resource commitment were evaluated quantitatively in appropriate units, and the emplacement methods ranked accordingly. The remaining factors were evaluated qualitatively by assessing the performance of the emplacement method against the evaluation factor. The performance ratings used are good (G), acceptable (A), acceptable with additional cost (A/AC), and unknown (U).[3]

As shown by the supporting analyses, the three emplacement methods differ primarily with respect to four factors: the length and volume of drifts required, heat flow from the waste into open ventilated drifts, the time required for waste emplacement or retrieval, and the extent to which available technology can be applied to drilling and waste emplacement/retrieval operations. Safety, measured in terms of worker hazard, is most strongly influenced by the first three factors. Dependability, evaluated in terms of reliability, flexibility, and scheduling criteria, is controlled by all four factors. The relative cost of each configuration, including construction and operations, resource commitment, and environmental impact, is most strongly influenced by the first factor, the length and volume of drifts required. The principal uncertainties in the comparison relate to the extent to which current technology is applicable to the equipment and operations required to emplace and retrieve waste. A summary of the evaluations is presented in Table III.[3]

Self-Shielded Package

The evaluation of the SSP concept indicates that it is the least desirable emplacement configuration and does not warrant further development. Costs are the highest, primarily because of material requirements for the waste package. The volume of mining needed, ventilation requirements, and potential operational problems associated with the presence of the waste package in the emplacement drift also contribute significantly to the cost. Potential worker injuries and fatalities are highest for this method, and estimated radiation doses exceed those associated with horizontal emplacement. The only inherent advantage of the SSP over other emplacement methods is that emplacement and retrieval equipment is relatively standard.

Vertical Emplacement

Placement of waste canisters in vertical boreholes is an acceptable method that satisfies the requirements of being safe and dependable. However, the relative cost is significantly higher than for horizontal emplacement because of the larger mined volume, additional ventilation required by higher drift temperatures, and the significantly longer period of time required for waste emplacement and retrieval. Potential worker hazards and radiation exposure are slightly greater than for horizontal emplacement. Environmental impact and the amount of diesel fuel used are greater than for the other two methods. The primary advantage of vertical emplacement is that the operations and equipment required to emplace waste are based on available technology. No unknown factors were identified in the evaluation, and the cost estimate is based on the most reliable information. On the basis of current information, the vertical emplacement method appears to be less desirable than horizontal emplacement.

Horizontal Emplacement

The placement of waste in long horizontal boreholes is the least costly of the three emplacement methods, and has the lowest number of potential injuries, fatalities, and radiation exposure. The primary operational advantages of horizontal emplacement result from the significantly lower mined volume, lower ventilation requirements during waste emplacement and retrieval, and the reduced time for waste emplacement. A major containment and isolation advantage may result from the longer period of high temperature and dry conditions that enhances waste package integrity. Environmental impact and resource commitment would be lowest due to the relatively small amount of mining required and better use of the rock to dissipate heat.

TABLE II

Preliminary Mining, Drilling, and Ventilation Characteristics Per 1,000 Canisters[a]

Characteristic	Emplacement Method: SSP	Vertical	Horizontal
Mining			
Drift Cross Section (Area)	3.7 × 6 m ($22\ m^2$)	Access 3.7 × 6 m ($22\ m^2$) Emplacement 6.7 × 6 m ($40\ m^2$)	3.7 × 6 m[b] ($22\ m^2$)
Total Length of Mined Drift[c]	12,550 m	Access 1,433 m Emplacement 11,108 m	740 m
Mined Material	278,610 m^3	478,354 m^3	20,428 m^3[d]
Drilling			
Total Drilling Length	0	7,620 m	5,555 m
Drilling Length per Canister	0	7.6 m	5.5 m
Canisters Emplaced	1,000	1,000	1,000
Drill Set-Ups per Canister	0	1	0.028
Ventilation[e]			
Tons of Refrigeration	3,433	2,098	63

a 3.4 kW/canister.

b Exclusive of alcoves.

c The central sections for both vertical and horizontal configurations are considered common and therefore are not included.

d Includes the additional mining of 4,000 m^3 of tuff, because current concepts include alcoves for horizontal emplacement.

e Total mine area is assumed to be ventilated in the horizontal configuration; one-half of the mine is assumed to be ventilated in the SSP and vertical configurations.

There are several uncertainties that need to be addressed in future studies before it can be determined whether horizontal emplacement is a dependable method for waste emplacement. The uncertainties are associated with horizontal borehole drilling and with emplacement and retrieval of waste canisters. Developmental programs conducted to date suggest that equipment and operations can achieve design goals, but selection of horizontal emplacement as the waste emplacement method requires the demonstration of the necessary equipment and procedures.

RECOMMENDATIONS

1. The self-shielded package should be given no further consideration for disposal of high activity wastes.

2. No significant additional design effort should be expended on vertical emplacement until comparably detailed information regarding horizontal emplacement has been developed.

3. Additional data and information should be developed regarding the feasibility of horizontal emplacement. Prototype equipment for drilling and lining horizontal boreholes and for emplacement and retrieval of the waste canisters, should be developed and tested.

TABLE III

Comparison of Alternatives[a] Per 1,000 Canisters[3]

Criteria	Emplacement Method SSP	Vertical	Horizontal
Reliability			
Thermal Hydrology	U	A	G
Thermal-Structural Stability	A/AC	A/AC	A/AC
Mining Drifts	G	A	G
Boreholes	NA	G	U
Ventilation--Emplacement	A/AC	A	G
Ventilation--Retrieval	A/AC	A	G
Emplacement Equipment	G	A	U
Retrieval Equipment			
Before Backfilling	G	A	U
After Backfilling	A/AC	A	U
Backfill at Emplacement	A/AC	A	A
Backfill at Closure	U	A/AC	A
Flexibility			
Waste Package Fabrication	A/AC	G	A
Waste Package Materials	A/AC	G	A
Thermal-Structural Stability	A/AC	A	G
Boreholes	NA	G	A
Ventilation--Emplacement	A/AC	A	G
Ventilation--Retrieval	A/AC	A	G
Emplacement Equipment	G	A	U
Retrieval Equipment	G	A	U
Backfill at Emplacement	A/AC	A	G
Backfill at Closure	U	A	G
Worker Hazards			
Injuries	47.2	14.7	11.0
Fatalities	0.34	0.16	0.08
Radiation Doses (man-rem)	3.5	4.7	1.1
Environmental Impact			
(m^3 of spoil)	278,610	478,354	20,428
Resource Commitments			
Steel (mt)	58,378	0	243
Diesel Fuel (L)	642,740	1,400,940	288,440
Power (million kWh)	208.2	156	44.9
Scheduling			
Mining Drifts	G	G	G
Boreholes	NA	G	U
Emplacement Equipment	G	A	U
Retrieval Equipment	G	A	U
Backfill at Emplacement	A/AC	A	A
Relative Cost ($ thousands)			
Backfill at Emplacement	>82,400[b]	33,319	10,128
Backfill at Closure	>82,400	34,086	10,482

[a] Good (G), Acceptable (A), Acceptable with Additional Cost (A/AC), Unknown (U), Not Applicable (NA).

[b] Costs do not include backfilling of access drifts.

REFERENCES

1. Code of Federal Regulations, Title 10, Energy, Chapter 1, Nuclear Regulatory Commission, Part 60, "Disposal of High-Level Radioactive Wastes in Geologic Repositories" (January 1984).

2. L. W. SCULLY, Sandia National Laboratories, letter to A. J. Rothman, Lawrence Livermore National Laboratory (August 11, 1982).

3. H. F. GRAM et al., "A Comparative Study of Radioactive Waste Emplacement Configurations," SAND83-1884, Los Alamos Technical Associates, Inc. (September 1983).

4. N. E. BIXLER et al., "Comparison of Waste Emplacement Configurations for a Nuclear Waste Repository in Tuff: I Thermal Analysis," SAND83-0860 (1983).

5. D. P. FLANAGAN, "Comparison of Waste Emplacement Configurations for a Nuclear Waste Repository in Tuff: III Thermal-Mechanical Analysis," SAND83-2114 (1983).

6. L. A. MONDY et al., "Comparison of Waste Emplacement Configurations for a Nuclear Waste Repository in Tuff IV. Thermo-Hydrological Analysis," SAND83-0757 (August 1983).

7. K. D. YOUNG and L. W. SCULLY, Sandia National Laboratories; A. FISK and P. DEBAKKER, Foster-Miller Associates, Inc.; J. FRIANT and A. ANDERSON, The Robbins Company; "Equipment for the Emplacement of Heat-Producing Waste in Long Horizontal Boreholes," SAND82-1844C, paper presented at 1983 Waste Management Symposium, Tucson, Arizona (March 1983).